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INTEGRATED COST AND SCHEDULE RISK ANALYSIS USING MONTE CARLO SIMULATION OF A CPM MODEL

TCM Framework: 7.6 – Risk Management

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SCOPE

This recommended practice (RP) of AACE International defines the integrated analysis of schedule and cost risk to estimate the appropriate level of cost and schedule contingency reserve on projects. The main contribution of this RP is to include the impact of schedule risk on cost risk and hence on the need for cost contingency reserves. Additional benefits include the prioritizing of the risks to cost, some of which are risks to schedule, so that risk mitigation may be conducted in a cost-effective way, scatter diagrams of time-cost pairs for developing joint targets of time and cost, and probabilistic cash flow which shows cash flow at different levels of certainty.

The methods presented in the RP are based on integrating the cost estimate with the project schedule by resource-loading and costing the schedule's activities. The probability and impact of risks/uncertainties are specified and the risks/uncertainties are linked to the activities and costs that they affect. Using Monte Carlo techniques one can simulate both time and cost, permitting the impacts of schedule risk on cost risk to be calculated.

These methods can be used both by the contractor and the owner. The contractor usually has a more detailed schedule and understanding of resource allocations used to put the costs into the schedule. The owner may use a more summary schedule and summary notion of resources, but still is able to put the costs into the schedule at a summary level. In fact there are many risks to the owner that do not affect the contractor as risks. Also, the contractor will not know about some of the owner's risk, such as having insufficient resources. In the case of joint venture owners the JV is often a marriage of convenience of disparate organizations with risks arising from different goals and methods.

This RP is consistent with the *Total Cost Management (TCM) Framework Section 7.6 Risk Management*. In particular, the entry in the *TCM Section 7.6.2.2 Identify and Assess Risk Factors*, highlights the fundamental "risk factors (or drivers) are events and conditions that may influence or drive uncertainty (i.e., either opportunities or threats) in asset or project performance." This RP uses the same approach, starting with the RP section *Simulating Using Risks as Drivers* and illustrating the method in the case study.

PURPOSE

This RP is intended to provide guidelines (not a standard) for integrated cost and schedule risk analysis which is generally considered to be good.

It is based on the recognition that some resources such as labor, rented equipment (e.g., drill rigs, cranes) and level-of-effort (LOE) support (e.g., project management team or quality/safety staff) will respond to risks to schedule because they cost more if they are engaged on the project longer than planned because of schedule delays. This method has been applied to cost and schedule risk in many industries and in commercial as well as governmental projects, so it is generic. One finds in applications of integrated cost-schedule risk analysis that some of the most important cost risks are actually viewed by project participants primarily as risks to the schedule that indirectly extend the use of resources. Applying the methods described in this recommended practice will highlight the identity and mechanism by which risks to schedule might cause cost risk.

This recommended practice describes an improvement in cost risk analysis over the traditional methods that address cost risk without explicit reference or, indeed, any reference at all to the project schedule and its risk. In this analysis the interaction between schedule risk and cost risk is modeled explicitly to develop several results; (1) the schedule contingency reserve, (2) the cost contingency reserve, (3) the joint probability distribution of project cost and schedule, (4) the priority risks leading to the need for these reserves of time and budget, and (5) prioritization of project risk, which can lead to efficient actions to mitigate both time and cost risk.

The platform of this analysis is a cost-loaded project schedule. One may use a summary schedule that is complete and integrated with logic end-to-end or a detailed project schedule. The budget (estimates made without padding for risk) is assigned to the activities using resources that may be summary in nature (e.g., construction, detailed engineering or procurement) or detailed. An analysis of the effect of schedule uncertainty on the impact of cost inflation may or may not be required.

Monte Carlo simulation is the most commonly used approach to analyzing the impact of multiple risks on the overall project schedule or cost risk. Simulating a resource-loaded project schedule derives both schedule risk and the cost risk implications in the same simulation. The main benefit of this RP is to the estimate of cost risk, since the schedule risk analysis in this setting is no different from a schedule risk analysis done without the involvement of resources or costs.

The risk analysis described below is correct only for the current plan, represented by the schedule. The project contingency reserve of time and cost that are the main results of this analysis apply if that plan is to be followed. Of course project managers have the option of re-planning and re-scheduling in the face of new facts, in part by mitigating risk. This analysis identifies the high-priority risks to cost and to schedule, which assist the project manager in planning further risk mitigation. Some project mangers reject the results and argue that they cannot possibly be so late or so overrun. Those project managers may be wasting an opportunity to mitigate risk and get a more favorable outcome.

BACKGROUND

Schedule risk has typically been ignored in assessments of cost risk. More recently cost risk analyses have included attempts to represent uncertainty in time, but usually these analyses occurred outside of the framework of the project schedule.

Only recently have the tools been available to include a full analysis of the impact of schedule uncertainty on the uncertainty in cost. The Monte Carlo tools first calculated labor cost proportional to the duration of activities. This was not a complete assessment of cost risk because it ignored other cost-type risks that are not related to schedule such as risks affecting the labor-type resources' burn rate per day and the uncertainty in equipment or material cost.

New tools have been developed that allow non-labor resources to vary in cost, as well as modeling uncertain daily rates (burn rates) for labor-type resources. This is not to say that the new software simulation tools are perfect, just that they are at a stage of development that warrants presenting them in an RP.

RECOMMENDED PRACTICE

The integrated cost-schedule risk analysis has several inputs, uses specialized Monte Carlo simulation tools, and produces several valuable outputs. A key success factor that should be present is that the organization is "risk-aware," wants to know the truth about the risks to the project and views the risk analysis as an important input to project success.

Summary of Inputs

Inputs to the analysis include:

- A high quality project schedule, whether a detailed schedule or a summary schedule that represents all of the work, is completely logically linked, does not rely on constraints or lags / leads, has resources loaded, durations are unbiased estimates, and is updated – basically a schedule following recommended practice CPM scheduling.

- A contingency-free cost estimate, meaning that line items do not have padding built in to accommodate risk and there is no below-the-line contingency included.

- Good quality risk data – usually risks that have been identified during a qualitative risk analysis of the project leading to a list of prioritized risks, with probability and impact parameter data collected so that they fully represent the risks and are not biased. Other risk data might include probabilistic risk events that alter the project schedule by adding recovery activities not necessary if the risk does not occur. Without good-quality risk data that is specific to the project being modeled, very little useful information will be derived from this exercise and the conclusions drawn may be incorrect and misleading.

Summary of Tools

The main tool of analysis is a Monte Carlo simulation of the cost-loaded schedule. Monte Carlo simulation is standard practice in quantitative schedule and cost risk applications. Most software packages that simulate project schedules can be used to integrate cost and schedule risk in the same simulations, although some packages are more capable than others.

Other software applications may be developed in this new field of integrated risk analysis. It should be emphasized that this RP is written as the practice is developing rapidly.

Summary of Outputs

Outputs of an integrated cost-schedule risk analysis are:

- How likely are the project plan's cost and schedule targets to be met given the risk that may affect that plan?

- How much contingency of time and cost needs to be provided to meet the risk threshold or certainty target of the project management or other stakeholders?

- Which risks are most important to the achievement of the project schedule and cost estimate?

- Prioritization of the risk to the schedule and to the cost of the project is an important result. This is a list of prioritized risks results derived from the quantitative analysis and is therefore more accurate than the risk register list that was used as an input to the analysis.

- Risk mitigation actions can be taken based on the prioritized list of risk. These actions can be analyzed using the same risk model that produced the plan contingency reserves of time and cost.

- A unique and useful result is the finding of joint time-cost risk results, often shown as a scatter diagram of time-cost points calculated during the simulation showing the possibility of meeting both time and cost objectives jointly, the so-called joint confidence level (JCL).

- Analyzing the time and cost risk together also leads to a probabilistic cash flow over time that is affected by uncertain costs and uncertain schedules.

INPUTS

Inputs to integrated cost and schedule risk analysis must include the cost estimate where the monetary values are estimated without constraints, a CPM schedule with realistic durations and complete schedule logic that can produce the correct dates and critical paths when the durations change, and risk data.

The Cost Estimate

The cost estimate is a basic input to the risk analysis. Since the risk analysis calculates the probability of achieving the cost estimate and the cost contingency reserve, the cost needs to be stated without contingency embedded in or added to it. A good rule is to make the cost estimate, for each project element, the unbiased "most likely" estimate. This would include some provision for inefficiencies and productivity levels less than 100%, but would not include provision for risk events or uncertainties, since one goal of the risk analysis is to estimate the additional cost needed for risk or uncertainties. Note that the "most likely" estimate is the mode of a probability distribution of possible durations. This value is different from the 50th percentile ("P-50"), which is the median, and from the mean or average duration.

The cost estimate should be consistent with the schedule in terms of resources assumed, their productivity and other factors. One way for this to occur is to refer to the basis of estimate that has all of the assumptions, including schedule assumptions, made in the cost estimate build-up.

The cost estimate is generally built up using engineering estimates, reference to analogous projects, application of expert judgment, and information provided by suppliers and subcontractors as well as market surveys.

Some estimators are uncomfortable about stripping the contingency amounts from the estimate, but the Monte Carlo simulation will re-estimate the contingency reserve that is appropriate for: (1) the risks to the specific project's cost plan, and (2) the desired level of certainty of the project management and other stakeholders

In this recommended practice we will use a simple project as an example. It is a construction project estimated to cost $624 million over a 28-month period. The cost estimate is shown in Table 1 below:

Construction Project	
Activity	Cost Estimate ($ millions)
Approval Process	$ 2.1
Environmental	$ 5.4
Design	$ 46.0
Procurement	$ 210.8
Install Equipment	$ 7.7
Construction	$ 335.8
Integration and Test	$ 16.5
Total Estimated Cost	$ 624.2

Table 1 – Example Project Cost by Activity

The CPM Schedule

The platform for the integrated cost-schedule risk analysis is a cost-loaded CPM schedule. This is a change for many cost estimators and cost risk analysts who usually work from the spreadsheet that contains the cost estimate and its backup sheets. Cost estimators are usually unfamiliar with project scheduling, so this will be a new challenge, perhaps handled with close cooperation with the project's scheduler. However, to incorporate the schedule risk into the cost risk the schedule has to be taken into account directly and transparently.

For an integrated cost-schedule risk analysis (and for schedule risk analysis) a summary schedule that is integrated, includes representation of all the work, has activities properly linked with logic and includes enough detail to highlight the main project milestones may be used. Experience shows that schedules of 300 – 1,000 activities can be used in a risk analysis, even of projects as large as $10 billion, although some practitioners will choose to include more or fewer activities depending on the type and complexity of project. There should be enough activities to faithfully reflect the structure of the project schedule including levels of total float, and for the assignment of risks. There is a temptation to include too much detail in the analysis (detailed schedules of thousands of activities) or to simplify the schedule to very few (20 – 30) activities. These extremes should be avoided. The correct approach is a compromise which provides enough detail to help identify and quantify risks and their impacts and a level of simplification which protects against making extensive assumptions - many of which will be wildly incorrect.

A detailed schedule may be used but it has several limitations:

- It is usually too difficult to identify and correct for best practices a detailed schedule with many activities and logical relationships

- Applying resources to activities is more difficult for a detailed schedule than for a summary schedule, even if summary resources are used.

- Simulation of the detailed schedule with risks attached is often time consuming

The first task in the risk analysis of cost and schedule is to debug the schedule. The schedule needs to follow CPM scheduling recommended practices because it needs to calculate the milestone dates and critical paths correctly, both in the static critical path method (CPM) schedule and during Monte Carlo simulation

The scheduling principles that are particularly important to the success of a Monte Carlo simulation, and in fact to a critical path method schedule, include[1]:

- All work needed to complete the project must be represented in the schedule. This is needed because we do not know what the critical path or risk critical path will be *a priori*, and because for integration of cost and schedule risk we need to be able to assign all the project cost to appropriate activities.

- There should not be any open ends, called "danglers." This means that each activity except the first activity needs a predecessor to drive its start date and each activity except the final delivery needs a relationship from its finish date to a successor, as shown in Figure 1 below.

The schedule should not rely on constraints to force activities to start or finish by certain dates. It should use logic for this purpose and not artificially reduce or restrict Total Float. Date constraints can modify CPM networks until they merely function as a calendar.

- Lags and leads are appropriate only in limited circumstances and are generally to be avoided in project scheduling.

- The schedule should be statused and the risk data used should be relevant to the statused schedule. Of course if a really serious event occurs to change the project fundamentally the risk analysis should be revisited.

[1] These points are consistent with those found in GAO Cost Estimating and Assessment Guide, US Government Accountability Office, March 2009 (GAO-09-3SP), pp. 218-224

- The activity durations need to be unbiased estimates of the “most likely” duration in projects like this conducted by the organizations involved. That means that normal inefficiencies and realistic assumptions about labor productivity should be the basis of the durations. The assumptions underlying estimates of durations should be consistent with those made for the cost estimates, and a good place to check this is the basis of estimate (BOE). Both the cost and schedule estimates must be stripped of contingency due to the fact that the result from the risk simulation will be to "add contingency on top of contingency" creating an unrealistic and overstated amount of contingency required.

- The schedule must have resources loaded and costed for the integrated cost-schedule risk analysis. This will be discussed in the next section.

- It is good scheduling practice to review the total float values to make sure they are reasonable. Large float values may indicate incomplete logic and, perhaps, the need to introduce and logically link additional activities.

It should be noted that the scheduling requirements for schedule risk analysis and for high quality CPM schedules are the same. One way to look at schedule risk analysis is that it is “the rest of the story” to be told after a high quality schedule has been constructed. The results indicate when the project is likely to finish when risk is taken into account.

In this recommended practice, a simple schedule of a 28-month construction project is shown in Figure 1 below:

ID	Description	Remaining Duration	Start	Finish	Total Cost
0010	Project Start	0	*01-Jan-11		$0
0015	Approval Process	90	01-Jan-11	31-Mar-11	$2,070
0017	Project Sanction	0		31-Mar-11	$0
0018	Construction Permits	180	01-Apr-11	27-Sep-11	$5,400
0020	Design	200	01-Apr-11	17-Oct-11	$46,000
0030	Procurement of Equipment	360	18-Oct-11	11-Oct-12	$210,800
0070	Install Equipment	90	12-Oct-12	09-Jan-13	$7,650
0040	Construction of the Facility	460	18-Oct-11	19-Jan-13	$335,800
0050	Commissioning	100	20-Jan-13	29-Apr-13	$16,500
0060	Project Turnover	0		29-Apr-13	$0
TOTALS					$624,220

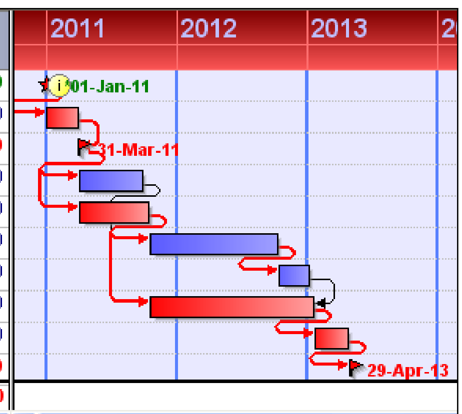

Figure 1 – Example Construction Project Schedule[2]

Resources Loaded into the CPM Schedule

Loading resources into the CPM schedule for the purpose of integrated cost-schedule risk analysis can be accomplished using summary resources; it does not require a detailed list of resources, though those might be available. Summary resources might include:

- Detailed engineering
- Direct construction labor
- Procured items
- Project management team
- Raw materials

[2] This figure and several others shown below are screen shots from Primavera Risk Analysis, formerly Pertmaster Risk Expert, now owned by Oracle.

- Installation
- Commissioning of equipment

These summary resources are not sufficiently detailed to perform resource leveling. Their purpose is to get the entire budget into the project schedule. Simple categories of resources that can be given budgeted values and placed on the activities they work on are needed. Resources used on the simple construction project are shown in Table 2 below:

ID	Description	Type	Default Loading
COMM	Commissioning	Labor	Normal
CONS	Construction	Labor	Normal
ENG	Engineers	Labor	Normal
ENV	Environmental	Labor	Normal
MGT	Management	Labor	Normal
PMT	Project Management Team	Labor	Normal
PROC	Procurement	Materials	Spread

Table 2 – Resources for Example Construction Project

In addition, the resources need to be tagged as "labor-type" or time-dependent resources or "material-type" or time-independent resources:

- "Labor-type" resources are those that will cost more if they work longer. These include contract labor, engineering labor, the project management team (a level-of-effort resource), and equipment that is billed by the day such as cranes, earth movers, drill rigs, installation barges and the like.

- "Material-type" resources include those that have uncertain costs but do not necessarily cost more if their activity takes longer. The main examples of these resources are manufactured equipment and bulk raw materials. Their costs may be uncertain but not because of time.

The purpose of resource loading the schedule for integrated risk analysis is to allocate the entire contingency-free budget to schedule activities. This approach will provide two attributes needed for the integration of cost and schedule risk:

- The entire budget is represented, so any change in the duration of activities supported by time-dependent resources will capture the cost effect of schedule uncertainty.

- Placing resources on individual activities will place the costs correctly in time, permitting the computation of probabilistic cash flow. The more the resources and costs can be placed on individual activities correctly, the more accurate the probabilistic cash flow will be.

An alternative method of applying resources to the schedule is to develop hammocks that span the activities that get the resources.

- A hammock is a good approach to take when applying level-of-effort (LOE) resources such as the project management team.

- However, establishing a hammock for, say, construction is a less than optimal way to handle labor-type resources. We know that construction labor starts at low levels but peaks, sometimes with thousands of workers each being paid by the day, and then tapers off as work is completed. Placing construction labor on several or even many construction activities will create the time-phasing of total construction labor.

Resources are applied to the schedule activities. Sometimes in doing this, the cost estimate and schedule have evolved largely independently of one another and the cost estimates are not consistent with the activity durations. It is important that if the estimate and schedule are initially developed independently of one another, that they are reconciled prior to holding the risk assessment. When costs are applied to the schedule, daily rates of resources will be implied. The problem with an unreconciled cost estimate and schedule is that the costs in the cost estimate and the durations in the schedule, which are presumably consistent when the baseline is established, quickly become inconsistent as the scheduled durations change with new information. . This inconsistency is revealed in inaccurate or unbelievable daily rates of resource expenditure when the resources are applied to the schedule, and these inconsistencies have to be resolved for the integrated cost-schedule risk analysis to be accurate.

The costs that result from placing the resources on the example project schedule are shown in Table 3.

Cost Estimate by Resource and Activity ($ thousands)								
Activity	PMT	MGT	ENV	ENG	PROC	CONS	COMM	Total
Approval	720	1,350						2,070
Environmental	900		4,500					5,400
Design	6,000			40,000				46,000
Procurement	10,800				200,000			210,800
Install Equipment	2,250					5,400		7,650
Construction	13,800					322,000		335,800
Commissioning	1,500						15,000	16,500
Total	35,970	1,350	4,500	40,000	200,000	327,400	15,000	624,220

Table 3 – Cost for Example Construction Project Showing Resources

<u>Risk Data Inputs</u>

First principles require that the risk of the project cost and schedule is clearly and directly driven by identified and quantified risks. In this approach the risks from the risk register drive the simulation. In more traditional approaches the activities and costs are given a 3-point estimate which results from the workings of potentially several risks. The influence of each risk cannot be disentangled. Also some risks will affect several activities, and it is difficult to capture the entire influence of a risk using traditional 3-point estimates of impact on specific activities. The risks that are chosen for the analysis are generally those that are assessed to be "high" and perhaps some "moderate" risks from the risk register. Risks are usually strategic risks rather than detailed, technical risks. There may be perhaps 20 to 40 risks, even in the analysis of very large and complex projects.

Once the risks are identified from the risk register, certain risks data is collected:

- The risks are quantified by their probability of occurring. In any iteration during the Monte Carlo simulation a risk will occur or not depending on its probability. For instance, a risk with a 40 percent probability of occurring will occur in a randomly-chosen 40 percent of the iterations.

- The risk also has an impact on the project if it does occur – impact is specified as a range of possible impacts. If the risk does occur, the durations and costs of the activities in the schedule that the risk is assigned to will be multiplied by the multiplicative impact factor that is chosen from the impact range for that iteration.

- The risks are then assigned to the activities and resources they affect.

Risks to project schedule and cost are generally classified in two different types:

- Risk events. These are events that may or may not happen, but if they do happen they will have a positive or negative impact on the cost or schedule or both.

- Uncertainties. These include ambiguities such as estimating error and uncertainties such as the level of labor productivity or the price of steel. These uncertainties are 100% likely to occur but their impact on the project cost or schedule is uncertain. These can be represented by the traditional 3-point estimates on duration or resources because they tend to apply across-the-board.

Collection of risk data relies on the processes of the risk identification and risk prioritization. The risk register is developed in a process:

- Risk identification and the collection of risk data are conducted in risk workshops and/or risk interviews. Devices such as the risk breakdown structure may be used to help participants think of risk that may be outside of their specific assigned area but which they know about.

- It is important during risk data collection to be alert to possible biases of the workshop or interview participants. Some people want to influence the results, while others genuinely do not understand the concepts or have some cognitive bias that has to be overcome. One tool is to include some people who are not directly involved in the project so they can be unbiased concerning the results. Another tool is to promise confidentiality to the participants so they can talk honestly and openly without fear that management will be displeased with them. Confidentiality is possible during risk interviews but not with risk workshops.

- Any cost or schedule estimating biases can be discovered during the workshop/interview process. Often the degree of estimating error will be added as an uncertainty (100% likely until project completion) and the ranges of estimating error might be asymmetrical, such as +20% and -10% from the estimate. Indeed the duration estimates may be determined to be the optimistic (short) value with most likely and pessimistic (long) values ranging upwards from there, based on optimism or customer/owner desire for an early finish.

- Risk assessment, sometimes called qualitative risk analysis, is the process of prioritizing identified risks for the project in question. The result of risk prioritization is to group the identified risks into high risk, moderate risk and low risk separately for time, cost, scope and quality. The results form the beginning of the risk register.

- The risk register risks that are "high" and "moderate" for time and cost form the basis of the quantitative risk data collection for the risk analysis of cost and schedule.

- The risk data collected are (1) the probability that the risk will occur on this project, (2) the impact on durations and costs, stated in percentage terms, if the risk occurs, and (3) the activities and costs that the risk will affect, if it occurs.

<u>Other Risk Data Required</u>

The degree of correlation between the activity durations has long been viewed as being important for understanding and estimating correctly project cost risk analysis. Correlation arises if one risk affects two (or more) activities that have time-dependent resources or if a risk affects the cost of two time-independent resources. If a risk occurs during an iteration the affected activities would <u>all</u> take more time and cost more – they become correlated in time and cost. The degree to which their durations are longer and shorter <u>together</u> is called correlation. If the activities' durations are not correlated they are called "independent." Correlation causes long activity durations and costs to reinforce each other during the project's execution, leading to potentially very long schedules. Correlation can lead to short durations occurring together. With cost estimates this could cause cost underruns. With schedules, however, the effect of the logical structure and parallel paths mitigates the possibility of schedule overruns. Estimating correlation coefficients using expert judgment is known to be difficult and problematic. Using risks to drive the simulation as discussed in this RP solves this correlation problem. It models the way correlation occurs by assigning risks to activities to drive the risk analysis so we do not have to estimate correlation coefficients. Project risks are generally stated at a strategic level and are independent of each other, although the simulation software will allow different risks to occur together if their existence is thought to be correlated.

Probabilistic branching or existence risk requires another type of risk data, the probability that an activity and its cost will exist on this project. Some risks may cause activities to occur only if the risk occurs. Such events as failure of a test or commissioning activity, if they occur, may require new activities such as finding the root cause of the failure, determining the recovery plan, executing the recovery plan and retesting the article. Most schedules do not include these risk recovery activities that may not occur at all. These activities will all take time and increase project cost. They can be inserted in the schedule as probabilistic branches or existence activities with time and cost implications if they occur. The data needed is the probability that they occur. This value is often under-estimated since people do not like to think of project testing or commissioning failure.

Simulation Using Risks as Drivers

In the simple example used in this RP, the risks' impacts are specified as ranges of multiplicative factors that are then applied to the duration or cost of the activities to which the risk is assigned.

The risks operate on the cost and schedule as follows:

- A risk has a probability of occurring on the project. If that probability is 100% then the risk occurs in every iteration. If the probability is less than 100% it will occur in that percentage of iterations, and each iteration, chosen at random by the computer program has the same probability that the risk will occur.

- The risks' impacts are specified by 3-point estimate. In the application used here, the impacts are multiplicative, so a schedule risk will multiply the duration of the activity that to which it is assigned. The 3-point estimate, for instance of low 90%, most likely 105% and high 120%, is converted to a triangular distribution. For any iteration the software selects an impact multiplicative factor at random from the distribution. For that iteration the multiplicative factor selected multiplies the duration of all the activities to which the risk is assigned.

- The cost risk factor is applied differently depending on whether the resource is labor-type or equipment-type.

    - For a labor-type resource, the cost risk factor varies the daily burn rate, representing more or fewer resources applied per day. Of course for these resources, their total cost is also affected by the uncertainty in the duration, but they may cost more or less even if their durations are as scheduled.

    - For equipment-type resources the cost risk factor varies the total cost since for these resources the cost may be uncertain but it is not affected by time.

Simulation Tools

Monte Carlo simulation is the most commonly applied method for conducting quantitative risk analysis. It is extremely difficult or even impossible to mathematically extend the properties of a complex CPM schedule into a single equation that could be used to predict the results of several risk events in a schedule. That is why Monte Carlo analysis has been used to estimate the results. A Monte Carlo simulation calculates the possible project cost and schedule values that may result from individual risks and translates them into project-level cost and schedule risk results. It allows the user to:

- Determine the likelihood of finishing on time and on budget
- Calculate the contingency reserve of time and cost to provide an acceptable level of certainty for stakeholders, and
- Identify the main risks to cost and schedule for the next phase, risk mitigation.

It is not known which risks will occur on any specific project. Since we do not know whether any risk will occur on any specific project or what its impact will be, we cannot tell when a project will finish or how much it will cost. We can only tell probabilistically when the project might finish and how much it might cost. In addition the risk analysis includes the impact of uncertainty such as errors in estimating activity durations or costs of project elements, which has a 100% chance of occurring but may result in a range of possible values.

Suppose the simulation contains 3,000 iterations – separate runs using randomly-selected risk data – and creates 3,000 pseudo-projects. Each of the 3,000 projects could be ours, since it is based on a different combination of risks applied to our project schedule and cost. These different combinations of input data generally compute different completion dates and project costs. Any of these date and cost results could be the project under analysis, but we cannot tell which one. The Monte Carlo simulation provides probability distributions of cost and schedule from which we can make probabilistic statements about our project.

A Monte Carlo simulation is, fundamentally, a “brute-force” way to determine the impact of risk on overall cost and schedule, because it runs (simulates) the project multiple (thousands) times with different inputs for the risks on each run (iteration), collects the data and displays histograms of the possible results.

The results of the Monte Carlo simulation assume the current plan is followed but may experience a number of risks’ occurring. In reality, project managers will alter their project plan if risks occur. CPM scheduling and risk analysis will never mirror the multiple changes that project managers implement as a result of risk, although we can model some of those changes using probabilistic branching and conditional branching.

OVERALL PROJECT INTEGRATED COST-SCHEDULE RISK ANALYSIS CASE STUDY

The following is a sample case study for illustrational purposes only. All values and assumptions used in the following example are based on hypothetical instances and may not be applicable to your situation. Suppose there is a project with the activities shown in Figure 1 above and resources/costs as shown in Table 1 and assigned to the activities as shown in Table 3 above. Also, suppose we have identified risks through workshop or interviews and have elicited the probability and time/cost impacts as shown in Table 4 below. (These are general risks that are found in many projects. Each project will have specific risks that can be identified and quantified through these data gathering methods):

			Duration Impact Ranges			Cost Impact Ranges		
Risk ID	Risk Description	Prob.	Min	M L	Max	Min	M L	Max
1	S/C - Design Complexity may Challenge Engineers	40%	90%	110%	135%	100%	105%	110%
2	S -Site Conditions / Site Access may Slow Logistics	50%	100%	110%	125%			
3	S/C-Equipment Suppliers may be busy	60%	100%	105%	120%	100%	110%	120%
4	S - Capable Management may not be Assigned	40%	90%	105%	115%			
5	S -Environmental Agency May be Slow	50%	95%	110%	135%			
6	S - Activity Duration Estimates is Inaccurate	100%	90%	105%	115%			
7	C - Cost Estimate is Inaccurate	100%				95%	105%	115%
8	S/C Key Engineering Personnel may be Unavailable	65%	95%	105%	120%	90%	100%	110%

Table 4 – Example Risks and their Parameters for the Case Study

After the risks are listed and their parameters quantified they need to be assigned to the activities and their resources. For this case study the risks are assigned according to Table 5:

	Activities						
Risks	Approval Process	Environmental	Design	Procurement	Install Equipment	Construction	Commissioning
S/C - Design Complexity may Challenge Engineers	X		X				
S -Site Conditions / Site Access may Slow Logistics						X	X
S/C-Equipment Suppliers may be busy				X			X
S - Capable Management may not be Assigned	X					X	X
S -Environmental Agency May be Slow		X					
S - Activity Duration Estimates is Inaccurate	X		X	X	X	X	X
C - Cost Estimate is Inaccurate	X		X	X	X	X	X
S/C Key Engineering Personnel may be Unavailable	X	X	X	X	X	X	X

Table 5 – Assigning Risks to Activities

The schedule histogram for the case study is below in Figure 2. It shows that the deterministic date of 29 April 2013 is about 4% likely to be achieved following the current plan and without further risk mitigation actions. Next, we will assume that the project stakeholders have agreed that their acceptable level of confidence is at the 80th percentile. At that point, it is 80% likely that the current project plan with all of its risks will finish on that date or earlier, and with that cost or less. Of course stakeholders may not want to be explicit about its target percentile, but an organization needs to specify its risk tolerance or threshold for each project (or over all projects as a policy).

At the P-80 the project finishes on 26 November 2013 or earlier and needs about a 7-month contingency reserve of time. These results are shown in Figure 2 and in Table 6.

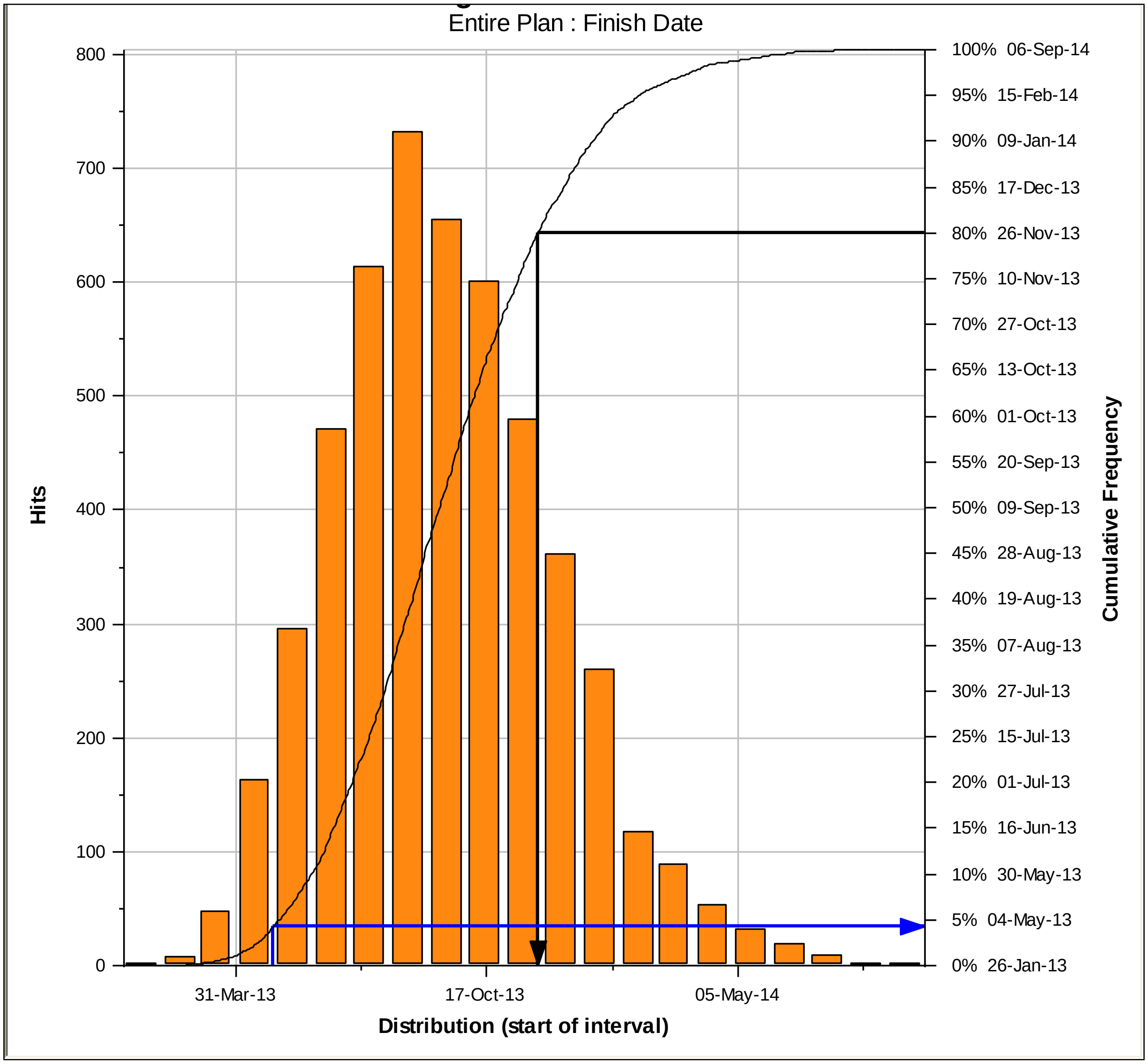

Figure 2 – Histogram with Cumulative Distribution (S-Curve) for the Project Completion Date

Summary Schedule Risk Analysis Results Example Construction Project						
Scenario		Schedule Probabilistic Results				
Deterministic	29-Apr-13	P-5	P-50	P-80	P-95	Spread
Prob. Deterministic	4%	4-May-13	9-Sep-13	26-Nov-13	15-Feb-14	P-95 to P-5
All Cost and Schedule Risks		Months				
Difference from Deterministic		0.2	4.4	6.9	9.6	9.4

Table 6 – Summary Schedule Risk Analysis Results for the Example Construction Project

The cost risk results, including the impact on cost of schedule risk, indicate the need for a contingency reserve of cost of about $169 million or 27% at the 80th percentile (P-80). At that level there is an 80 percent probability that the project will cost $793 million or less, given the risks and following the current plan. These results are shown below in Figure 3 and table 7:

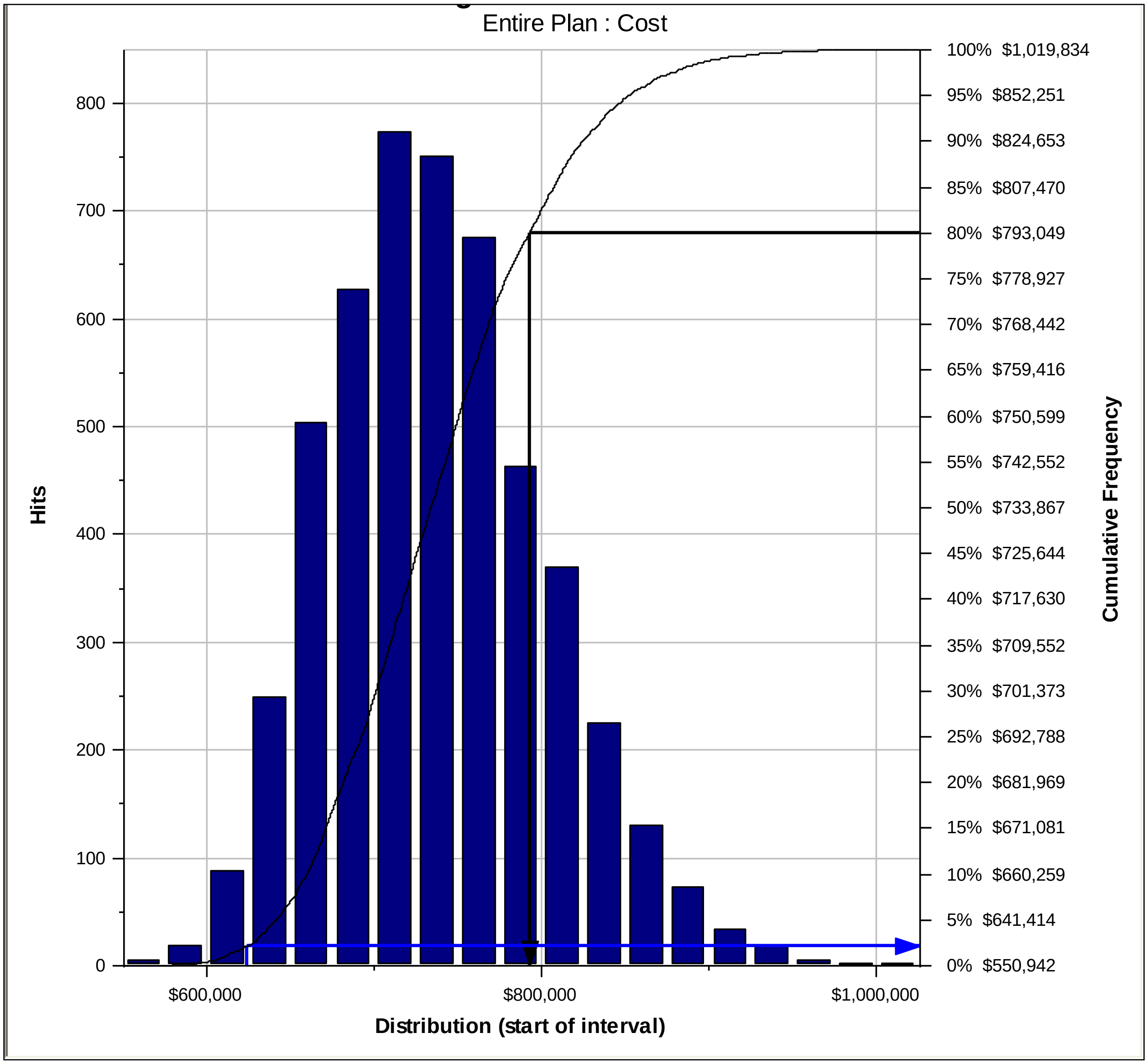

Figure 3 – Histogram with Cumulative Distribution (S-Curve) for the Project Cost

Summary Cost Risk Analysis Results Example Construction Project ($ millions)						
Scenario		Cost Probabilistic Results				Spread
Deterministic	624	P-5	P-50	P-80	P-95	P95-P5
Prob. of Deterministic	2%	641	734	793	852	
Difference from Deterministic $		17	110	169	228	211
Difference from Deterministic %		3%	18%	27%	37%	

Table 7 – Summary Cost Risk Analysis Results for the Example Construction Project

Enhanced Cost Risk Results

We can find out whether cost-type risks or schedule-type risks are more important in determining the cost contingency to, say, the P-80 point. The source of the cost contingency can be discovered by eliminating all schedule risks to compute the marginal impact of cost risks, then repeating the process by eliminating the cost risks and computing the impact of schedule risks on contingency. The results are shown below in Table 8.

Decompose the Cost Contingency at the P-80		
	P-80	Marginal Impact
	($ millions)	
Contingency-Free Cost Estimate	624	
All Risks	793	
Cost Risks Only	702	78
Schedule Risks Only	727	103
Total Contingency All Risks	169	
Note: Amounts do not add at P-80, only at means		

Table 8 – Cost, Schedule and Interaction Effects

Table 8 shows that if only cost risks were present (the schedule is static) the cost contingency at the P-80 could be $78 million whereas if only schedule risks were included (no cost risk on burn rate or on procurement / materials) the contingency needed at the P-80 is $103. These results depend on the case study assumptions, but in many examples of integrated cost and schedule risk conducted on projects the majority of the risk to cost arises from uncertainty in the schedule as it does in the example in this RP.

Correlation between Cost and Schedule

The time-cost scatter diagram shown below in Figure 4 is diffuse because there are some time-independent cost risks that affect the burn rate of labor-type resources and total cost of procured items. The cross-hairs shown on the diagram cross at the deterministic point of 29 April 2013 and $624.2 million. The sparse collection of points in the lower-left quadrant indicate that there is only a 1% chance that this project will satisfy both cost and schedule targets without contingency reserve. There is also a 95% chance that this project, if the current plan were pursued to the end and with the known and quantified risks we have chosen, will overrun both cost and time objectives.

There is clearly a positive slope running through the cloud or "football (US version) chart" showing the strong impact on cost of schedule risks. The correlation between time and cost is 77% in this case study, which is somewhat higher than is common in these analyses.

The cross-hairs can be re-positioned to indicate other specific joint probabilities.[3]

[3] NASA is using the joint confidence level of 70%. That is, a point where there is a 70% chance of meeting both cost and schedule. Of course there are many time-cost pairs that satisfy this requirement.

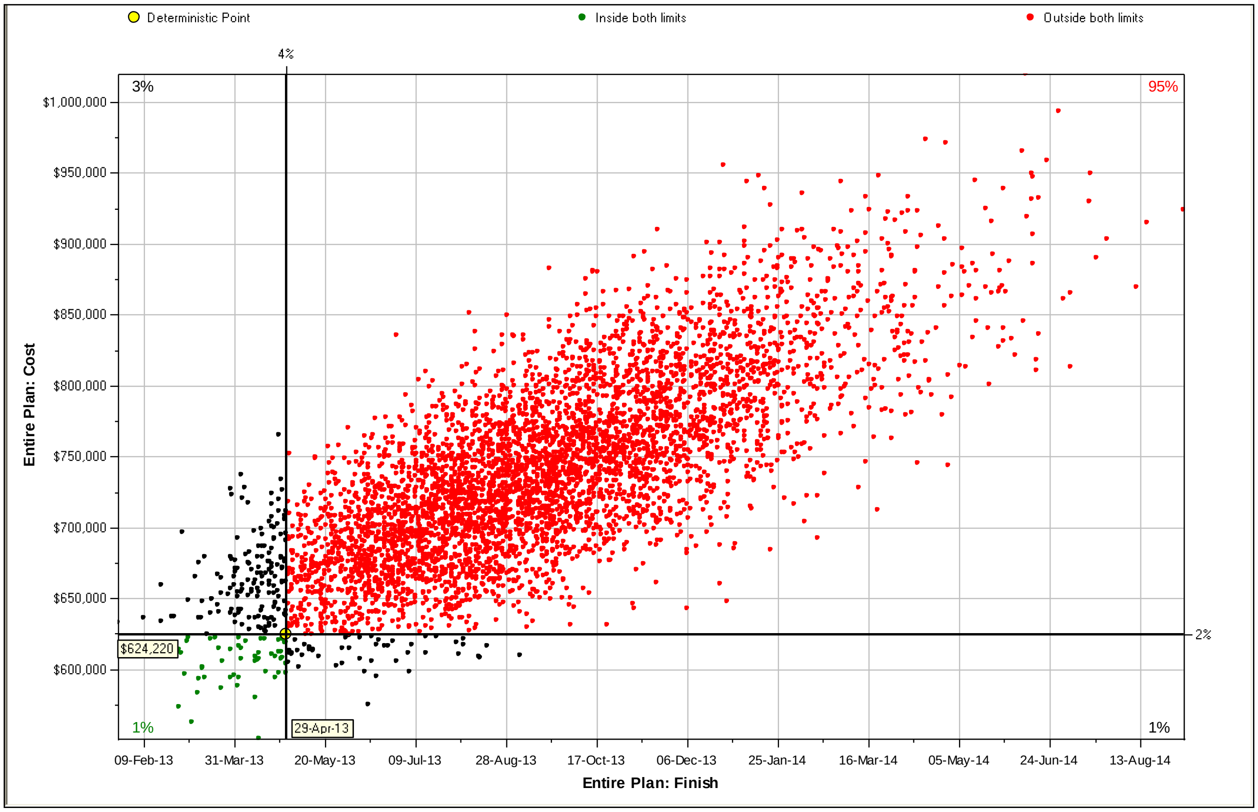

Figure 4 – Cost and Time Results from the Simulation with Crosshairs indicating the Deterministic Project Plan without Contingency

One can calculate the probabilistic cash flow because both cost and schedule risks are represented in the schedule. The probabilistic cash flow helps organizations that want to know the probability that they can work within annual budgets. Figure 5 compares the P-80 cash flow to the deterministic cash flow (without contingency) shown in the risk-free schedule plan. The time-cost cloud or football is the same as in Figure 4 above but it is placed on a time-scale and a cost scale with origins from the beginning of the project.

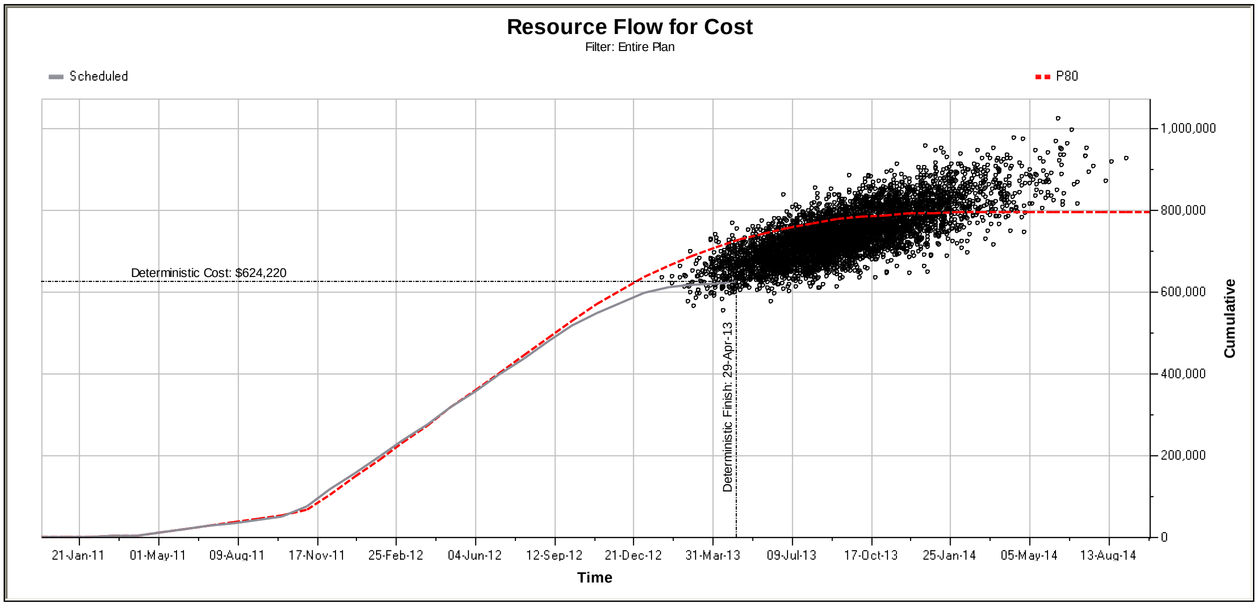

Figure 5 – Probabilistic Cash Flow showing the P-80 Cash Flow by Month Compared to the Plan's Deterministic Cash Flow

Probabilistic Branches or Project-Busting Risks

Some risks will add activities to the project schedule if they occur, and hence will add time and cost. Most often a project plan assumes that the project goes well and that there are no major problems. It is also common that something goes wrong leading to a mandatory change in plans as the project tries to recover from a discontinuous event. An example of this problem might be the failure of the project at commissioning or final testing. Any test can be failed – in fact that is why tests are required – and if the product fails the test certain activities must be added to the project's schedule. These activities might be:

- Determine the root cause of the failure.
- Decide what to do (e.g., send the equipment back to the manufacturer, repair it on-site or take a different approach, are all possible actions).
- Implement the action. Repair or replace the failing part.
- Re-test and, hopefully, pass the test this time.

Some of these steps may have short durations such as taking a spare part off the shelf and testing it. Others can take months if a part needs to be re-manufactured. These activities will all have cost implications. If the test is at the end of the project, before turnover, it will be on the critical path and hence will delay the project.

One common characteristic of these activities, though, is that they are almost never found in the initial project schedule. However, in risk analysis the possibility of test failure, or some other discontinuous uncertain event, must be modeled using existence risks or probabilistic branching.

Suppose that the commissioning activity might uncover a problem that takes time to fix. Simple changes can be made in the project schedule to accommodate this potentially project-busting occurrence. We cannot use the risk drivers that are assigned to existing activities since those activities are not in the schedule. New activities are created, though in the current schedule they are given a duration of zero (0) days since the failure of commissioning is possible but not certain. An implementation of probabilistic branching is shown in Figure 6.

ID	Description	Remaining Duration	Start	Finish	Total Cost	Minimum Duration	Most Likely	Maximum Duration
0010	**Project Start**	0	*01-Jan-11		$0			
0015	Approval Process	90	01-Jan-11	31-Mar-11	$2,070			
0017	**Project Sanction**	0		31-Mar-11	$0			
0018	Construction Permits	180	01-Apr-11	27-Sep-11	$5,400			
0020	Design	200	01-Apr-11	17-Oct-11	$46,000			
0030	Procurement of Equipment	360	18-Oct-11	11-Oct-12	$210,800			
0070	Install Equipment	90	12-Oct-12	09-Jan-13	$7,650			
0040	Construction of the Facility	460	18-Oct-11	19-Jan-13	$335,800			
0050	Commissioning	100	20-Jan-13	29-Apr-13	$16,500			
0140	Diagnose Problem	0	30-Apr-13	29-Apr-13	$0	30	50	100
0130	FIXIT	0	30-Apr-13	29-Apr-13	$0	50	100	200
0120	Re-Commission	0	30-Apr-13	29-Apr-13	$0	60	80	100
0060	**Project Turnover**	0		29-Apr-13	$0			
TOTALS					$624,220			

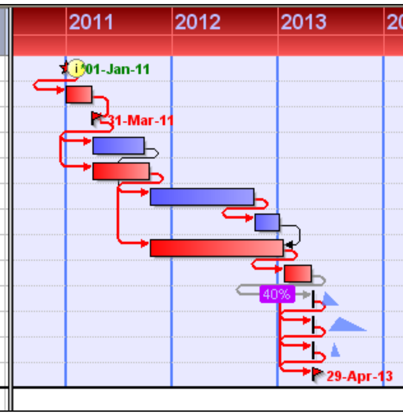

Figure 6 – Activities Added to Provide for a Risk That Commissioning May Not Complete Successfully

In Figure 6 there is a 40% probability that commissioning will not complete successfully. The durations of the three new activities, diagnose problem – FIXIT – re-commission – are set to zero so if the project passes its commissioning these extra activities add nothing to cost or to schedule. However, if it does happen, these activities exist and have been given traditional 3-point estimates of duration – since their initial duration is zero days we cannot apply risk drivers to these activities.

The schedule results for adding a probabilistic branch are shown in Figure 7. Notice that the schedule is slightly bi-modal, with 60% of the results in the left-hand part of the distribution and 40% in the right-hand part. There is a bit of a “shoulder” in the cumulative distribution at 40% that follows the specification that the commissioning will fail 40% of the time.

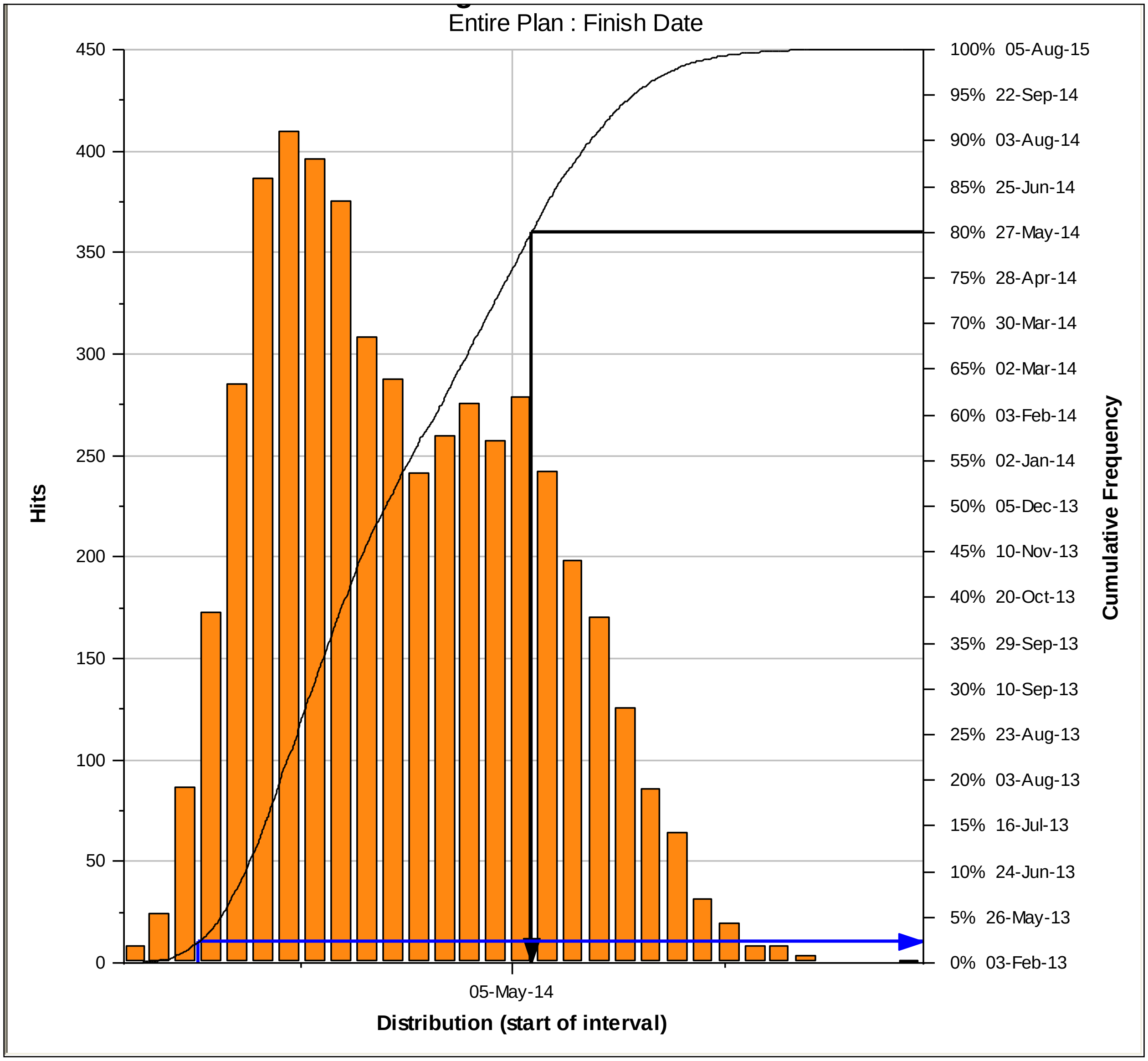

Figure 7: Schedule Impact of Probabilistic Branch on Commissioning vs. No Branch

The cost of the project goes up at the P-80 since resources are placed on the probabilistic branch. The impact on cost and schedule of a 40% probable problem during Commissioning, with the parameters shown here are shown below in Table 6.

Effect on Cost and Schedule Risk of Possible Commissioning Failure			
	No Commissioning Risk	Commissioning Risk @ 40%	Difference
Schedule			Days
P-80 Date	26-Nov-13	27-May-14	182
Probability of 29 April 2013	4%	2%	-2%
Cost	$ millions		
P-80 Cost	$ 793.0	$ 829.5	36.5
Probability of $624,220	2%	1%	-1%

Table 6 – Schedule and Cost impact of a 40% Probable Commissioning Risk

Prioritized Risks to Schedule and Cost

If the risk results for schedule and for cost are not "acceptable" to the customer, the analyst can prioritize the risks for the project manager who will want to mitigate the highest-priority risks.

- For schedule risk we need to identify the most important risk by taking each risk out entirely (make the probability = 0%) and re-run the simulation to determine the P-80 date. Taking each risk out one at a time allows us to identify the risk that has the greatest marginal impact on the P-80 date. Then, we explore the remaining risks to see which of those is next-most-important, and so forth. Removing one important risk may expose other risks that then become important but were not so if the first risk still exists. This is a phenomenon of the schedule's logical structure.

- For cost risk this is done by taking each risk out of the project one at a time, computing the impact to the P-80 cost compared to the all-in results, and finding the risk that has the largest impact on the P-80 cost. It is logical to identify the schedule risks that have cost risk implications as described above but the list of the risks in order of priority may differ for time and for cost.

Table 7 below shows which risks (including the commissioning probabilistic branch) are the most important for schedule and Table 8 shows the risks in order of priority for cost.

Priority Schedule Risks			
Risk ID	Risks	P-80 Date	Contribution to the P-80 Contingency
	ALL RISKS INCLUDED	27-May-14	(Days)
Risks Removed			
9	S/C - May have Problems during Commissioning	13-Nov-13	195
8	S/C Key Engineering Personnel may be Unavailable	4-Oct-13	40
6	S - Activity Duration Estimates is Inaccurate	18-Aug-13	47
2	S -Site Conditions / Site Access may Slow Logistics	6-Jul-13	43
1	S/C - Design Complexity may Challenge Engineers	19-Jun-13	17
3	S/C-Equipment Suppliers may be busy	30-May-13	20
4	S - Capable Management may not be Assigned	6-May-13	24
5	S -Environmental Agency May be Slow	29-Apr-13	7

Table 7 – Highest Priority Risks to Project Schedule at the P-80 Level of Confidence

Priority Cost Risks			
Risk ID	Risks	P-80 Cost	Contribution to the P-80 Contingency
	ALL RISKS INCLUDED	829.5	
Risks Removed			
7	C - Cost Estimate is Inaccurate	788.3	41.2
9	S/C - May have Problems during Commissioning	750.4	37.9
8	S/C Key Engineering Personnel may be Unavailable	719.1	31.3
2	S -Site Conditions / Site Access may Slow Logistics	687.7	31.4
6	S - Activity Duration Estimates is Inaccurate	664.6	23.1
3	S/C-Equipment Suppliers may be busy	641.7	22.9
4	S - Capable Management may not be Assigned	632.6	9.1
1	S/C - Design Complexity may Challenge Engineers	625	7.6
5	S -Environmental Agency May be Slow	624.2	0.8

Table 8 – Highest Priority Risks to Project Cost at the P-80 Level of Confidence

The total contingency in this example, including the possibility of problems during commissioning, is $205.3 million.

Risk Mitigation using Prioritized Risks

If the results of the risk analysis example indicating a low chance of meeting the current budgeted costs are not 'acceptable' the first thing to recognize is the inaccuracy of the estimates, which is viewed as moderate at risk impact multipliers of 95%, 105% and 115%. However this risk is 100 % likely to occur, since estimating error is with us until project financial completion, and it is assigned to each activity in the project. The next item to be concerned about is the probability of problems during commissioning, which is also the highest schedule risk. The impact on cost is related to the impact on schedule of a possible failure of commissioning. The next largest item would be the unavailability of key engineering staff. Down the list at position five is the inaccuracy of the schedule.

In fact, in the simple example made up for this document, only the top risk to project cost is a pure cost risk. The other important risks are mostly schedule risks (some with cost risk components, see Table 4 above) that increase cost if their activities are longer than assumed in the schedule. These schedule risks may be missed or underestimated if the cost risk analysis does not explicitly handle the relationship of time and cost risk, as is shown in this RP. This case study finding that schedule risks are important in driving cost risk is also commonly found on large projects. It reinforces the benefits of integration of cost and schedule.

SUMMARY

Integrating cost and schedule risk into one analysis based on the project schedule loaded with costed resources from the cost estimate provides both: (1) more accurate cost estimates than if the schedule risk were ignored or incorporated only partially, and (2) illustrates the importance of schedule risk to cost risk when the durations of activities using labor-type (time-dependent) resources are risky. Many activities such as detailed engineering, construction or software development are mainly conducted by people who need to be paid even if their work takes longer than scheduled. Level-of-effort resources, such as the project management team, are extreme examples of time-dependent resources, since if the project duration exceeds its planned duration the cost of these resources will increase over their budgeted amount.

The integrated cost-schedule risk analysis is based on:

- A high quality CPM schedule with logic tight enough so that it will provide the correct dates and critical paths during simulation automatically without manual intervention.

- A contingency-free estimate of project costs that is loaded on the activities of the schedule.

- Resolves inconsistencies between cost estimate and schedule that often creep into those documents as project execution proceeds.

- Good-quality risk data that are usually collected in risk interviews of the project team, management and others knowledgeable in the risk of the project. The risks from the risk register are used as the basis of the risk data in the risk driver method. The risk driver method is based in the fundamental principle that identifiable risks drive overall cost and schedule risk.

- A Monte Carlo simulation software program that can simulate schedule risk, burn-rate risk and time-independent resource risk.

The results include the standard histograms and cumulative distributions of possible cost and time results for the project. However, by simulating both cost and time simultaneously we can collect the cost-time pairs of results and hence show the scatter diagram ("football chart") that indicates the joint probability of finishing on time and on budget. Also, we can derive the probabilistic cash flow for comparison with the time-phased project budget.

Finally the risks to schedule completion and to cost can be prioritized, say at the P-80 level of confidence, to help focus the risk mitigation efforts. If the cost and schedule estimates including contingency reserves are not acceptable to the project stakeholders the project team should conduct risk mitigation workshops and studies, deciding which risk mitigation actions to take, and re-run the Monte Carlo simulation to determine the possible improvement to the project's objectives.

Finally, it is recommended that the contingency reserves of cost and of time, calculated at a level that represents an acceptable degree of certainty and uncertainty for the project stakeholders, be added as a resource-loaded activity to the project schedule for strategic planning purposes.

REFERENCES

1. AACE International, Recommended Practice 10S-90, *Cost Engineering Terminology*, AACE International, Morgantown, WV, (latest revision).
2. Hollmann, John K., PE CCE, Editor, *Total Cost Management Framework: An Integrated Approach to Portfolio, Program and Project Management*, AACE International, Morgantown, WV, 2006.
3. Various project management standards describe this process. See: Guide to the Guide to the Project Management Body of Knowledge (PMBOK® Guide), Project Management Institute, 4th edition, 2009, Chapter 11; Project Risk Analysis and Management Guide (PRAM Guide), Association for Project Management (UK), 2004, Second Edition.
4. See: Tversky, A. and D. Kahneman (1974). "Judgment under Uncertainty: Heuristics and Biases." Science 185: 1124-31.

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